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Optimization of Build Time and Support Material Quantity for the Additive Manufacturing of Non-Assembly Mechanisms

Martin Hallmann[a,*], Stefan Goetz[a], Benjamin Schleich[a], Sandro Wartzack[a]

[a] *Engineering Design, Friedrich-Alexander-University Erlangen-Nuremberg (FAU), Martensstrasse 9, 91058 Erlangen, Germany*

Abstract

In the context of modern industrial manufacturing, Additive Manufacturing processes are gaining more and more importance. Thus, the required quantity of material as well as the production time, which is mainly influenced by the build time required for the layerwise manufacturing process, are decisive for a successful industrial application. At component level, various approaches for minimizing the build time and the quantity of material are discussed in literature and are yet implemented in commercial software tools for preprocessing, the so-called slicing software. However, there is a lack of suitable methods for expediting the manufacturing process of non-assembly mechanisms. Although the positions and orientations of the individual, mutually movable linkages of a mechanism, which are defined in the CAD model, have a significant influence on the resulting build time and quantity of support material, the optimization potential has remained untapped so far.

Motivated by this shortcoming, the paper introduces a method for achieving minimum build time and support material quantity using a metaheuristic optimization technique. By integrating a suitable slicing software in the optimization process, the analysis of build time and support material quantity is based on the machine code, which is adapted to the applied machine and its various settings of the process parameters. The novelty of the contribution can be found in the optimization of build time and support material quantity for the additive manufacturing of non-assembly mechanisms by determining an optimal positioning of the individual movable links for the manufacturing process. A parallel 3RRR mechanism serves as a case study to show the benefits and the applicablity of the proposed method.

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Keywords: Optimization; Additive Manufacturing; Non-assembly mechanisms; Build time analysis

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1. Motivation

Additive Manufacturing (AM) processes have rapidly evolved from a technically interesting, but economically unprofitable manufacturing process to one of the most promising key technologies of modern industrial manufacturing [1, 2]. In contrast to traditional processes, the various AM processes enable the manufacturing of individualized parts with complex shapes and internal structures at low manufacturing costs for small batch sizes [2].

Furthermore, the possibility of manufacturing an entire assembly in one single process step facilitates the manufacturing process, since a subsequent assembly step is thus omitted. As a consequence, whole assemblies with moveable parts can be manufactured as one single component. [2] In the Additive Manufacture of so-called non-assembly or as-built mechanisms, the arrangement, i.e. the orientation and position, of the individual components has a significant effect on the required support material quantity and the build time.

At component level, various approaches for minimizing the build time and the support material quantity are discussed in literature and are already implemented in commercial software tools. However, there is a lack of suitable methods for expediting the manufacturing process of non-assembly mechanisms. Motivated by this need, this paper introduces a method for achieving minimum build time and support material quantity using a metaheuristic optimization technique.

After reflecting the state of the art and research in section 2, a novel method for build time and support material quantity optimization is presented in section 3. While section 3.1 describes the general framework of the proposed method with its mathematical background, section 3.2 discusses its key elements in detail. The application to a planar parallel mechanism in section 4 shows its applicability and its benefits. Finally, section 5 summarizes the paper and gives a brief outlook on further research activities.

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* Corresponding author. Tel.: +49-9131-85-23224;
E-mail address: hallmann@mfk.fau.de (Martin Hallmann).

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Nomenclature

B	Build volume of manufacturing machine
eq	Equality condition
i	single part of mechanism
iq	Inequality condition
n	Total number of parts
obj	Objective function
Q	Support material quantity
T	Build time
$\vec{v}$	Location and orientation of part i
V_i	Volume of part i
$\vec{x}$	Decision variables
x_i	x-position of part i
y_i	y-position of part i
z_i	z-position of part i
ψ_i	Orientation of part i around x-axis
θ_i	Orientation of part i around y-axis
ϕ_i	Orientation of part i around z-axis
Ω	Volume of manufactured assembly

2. State of the art

In the beginnings of AM, the achievement of industrial maturity of the various new manufacturing processes was focused. Through continuous improvements and innovations, a number of selected processes were succesfully implemented in industry and are nowadays particularly used for Rapid Protoyping and Rapid Manufacturing [1, 2]. Besides numerous innovative application fields, the manufacturing of non-assembly products attracts the attention of research and industry [2]. Taking specific design guidelines into account, e.g. minimum joint clearances [3, 4, 5], the manufacturing of revolute joints [6, 7, 8, 9, 3, 4, 10, 11], universal joints [7, 8, 9, 3, 4] or spherical joints [7, 8, 10, 12] is studied in detail and is also successfully integrated in non-assembly mechanisms for robotic applications [8, 7]. In this context, the various manufacturing processes Selective Laser Sintering (SLS) [7, 8], Stereolithography [11], Photopolymer Jetting [9, 3, 10, 12] and Fused Deposition Modeling (FDM) [5, 4] are taken into account. Their choice in combination with the design of a product decide whether support structures are necessary to realize overhangs and undercuts [5]. While SLS, for instance, does not require any support structures, the production of non-assembly mechanisms using FDM necessitates the use of structures to separate the individual moving parts from each other. Depending on the type of support material, these structures can be removed mechanically or dissolved in a subsequent cleaning process as it is exemplarily illustrated in Fig.1 using the example of a revolute joint [5].

For a profitable industrial application of AM, both the **performance** and the **efficiency** are decisive [13]. While the performance is measured by key characteristics such as geometric accuracy, surface roughness or mechanical and tribological properties, the efficiency is primarily determined by the required build time and material quantity since both essentially bear the production costs [14, 13]. Depending on the choice of the individual process parameters, the part build orientation and the part geometry, the required **build time** can range from a few minutes to several hours [15]. In order to estimate or rather predict the required build time, two main computer-aided methods have established themselves: the so-called **detailed-analysis-** and **parametric-based build time estimators**. Detailed analysis-based build time estimation techniques use the information of the individual toolpaths for generating the part geometry layer by layer for forecasting the build time. This type of estimators is usually used in combination with suitable preprocessing software for the individual manufacturing processes. [16] In contrast, parametric-based estimators try to establish more general predictive models by using traditional and advanced techniques, e.g. artificial neuronal networks [17], taking theoretical and experimental information into account [16]. As a result of the great scientific efforts in the last years these computer-based methods can nowadays achieve a good compliance between the estimated and the real build time [18]. Both methods can be used for the build time analysis or rather prognosis but also for optimizing the build time of AM processes.

The optimization of the efficiency and performance of AM is mainly done employing stochastic optimization algorithms. Stochastic, metaheuristic optimization algorithms allow to solve complex, both single- and multi-objective optimization problems in reasonable computation times and are therefore suitable to deal with most of the problems from research and industry [19]. Thus, common metaheuristic single- and multi-objective optimization algorithms, such as Genetic Algorithm [20, 21, 22, 23, 24, 25], Particle Swarm Optimization [26], Teaching-Learning-Based Algorithm [27] and Multiobjective Genetic Algorithm [28] are used in literature to determine an optimal build part orientation of additively manufactured parts to reduce build time and support material or to optimize the part quality.

As a consequence, the automated optimization of build part orientation and the arrangement of individual parts on the build platform is implemented in common commercial and open-source preprocessing software for AM, such as Stratasys Insight™ or Autodesk® Meshmixer®. Although the potential of optimized part orientation in as-built assemblies is known [29], the majority of research activities is limited to single parts.

Therefore, an user-friendly method for the optimization of build time and support material quantity taking the part orien-

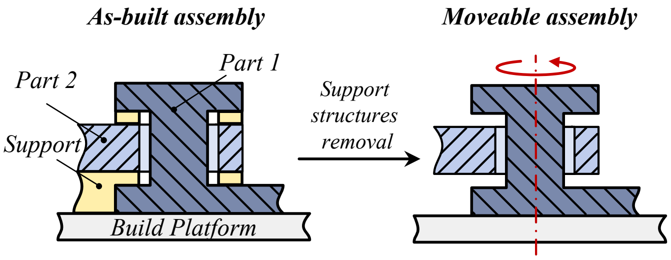


Fig. 1. Additive Manufacturing of non-assembly mechanisms by FDM using the example of a revolute joint.

tiation and position of the single parts in non-assembly mechanisms into account is missing so far.

3. Optimization of build time and support material quantity for as-built assemblies

In order to counter the lack of a suitable method for identifying an optimal design of a non-assembly mechanism for either the build time or the support material, a novel optimization method is presented in the following. After introducing the general framework including the mathematical background in section 3.1, the implementation of the method is described in section 3.2 in detail.

3.1. General framework

In contrast to traditional manufacturing processes, the geometry defined in the CAD model serves as the direct basis for the manufacturing process. While the build part orientation and the position of a part are usually defined in the subsequent preprocessing step in order to generate the toolpaths for the manufacturing machine, the orientations and positions of the individual parts in an as-built assembly are defined in the CAD system. The modification of the mating conditions applied between the different parts facilitates their relative positioning as well as orientating of adjacent parts. Since this allows the verification of the functionality of assemblies, the definition of mating conditions is mandatory during the setup of CAD models. In doing so, the required support material quantity as well as the build time are implicitly pre-defined. However, since the optimal part orientation and positions in an assembly are not readily apparent, an automized part orientating and positioning approach is needed to increase the efficiency by minimizing the build time and the support material quantity.

In general, the placement $\vec{v_i}$ of an individual part i can be described by its positions x_i, y_i, z_i and its orientations ψ_i, ϑ_i, φ_i in its respective body coordinate system:

$$\vec{v_i} = [x_i, y_i, z_i, \psi_i, \theta_i, \phi_i]^T. \tag{1}$$

Thus, the joints between the different parts constrain their feasible rigid body movements. As it is well known, the degree of freedom (DOF) of a whole assembly results from the sum of the remaining DOFs per part, which are not locked by the adjusted joints and the bearings. In order to guarantee the mobility of mechanisms they are usually kinematically underconstrained. Moreover, additively manufactured non-assembly mechanisms can have more DOFs than in installed state depending on the number of bearings to be included in the manufactured assembly. This fact is examplarily shown for a five bar linkage mechanism in Fig. 2. Assuming that the frame including three bearings with one rotational DOF, the DOF of the as-built assembly increases from one to four compared to the installed state of the mechanism.

The decision variables vector $\vec{x}$ for the optimzation includes all possible translations and rotations of the individual parts $\vec{v}_{i,red}$, which are not locked by a joint or a bearing:

$$\vec{x} = [\vec{v}_{i,red}, \ldots, \vec{v}_{n,red}]^T. \tag{2}$$

Depending on the objective in focus, the optimization problem can be formulated as a constrained single-objective optimization problem in order to minimize the build time T or rather the support material quantity Q:

$$\begin{aligned} \text{min} \quad & obj = T(\vec{x}) \text{ or } obj = Q(\vec{x}), && (3)\\ \text{subject to} \quad & V_i \cap V_j = \emptyset \quad \forall\, i, j = 1 \ldots n, i \neq j, && (4)\\ & \dim(\Omega) \leq \dim(B), && (5)\\ \text{with} \quad & \Omega = \{V_i \cup \cdots \cup V_n\}. && (6) \end{aligned}$$

The feasibility condition in equation (4) ensures that there are no volume intersections between the repositioned and reorientated parts. In addition, the volume of the rearranged assembly Ω with its parts $i = 1, \ldots, n$ must still fit in the build volume B of the machine which is ensured by equation (5).

The general workflow to solve the optimization problem defined in equation (3-6) is illustrated in Fig. 3.

Beginning with the initial part positions and orientations of the assembly, the optimization algorithm iteratively tries to find an optimal arrangement of the mechanism. For this purpose, the decision variables $\vec{x}$ are newly selected within their definition ranges in each optimization step and the positions and orientations of the parts are updated. Afterwards, the build time and the required support material quantity must be calculated with the help of a suitable estimator leading to the resulting objective obj. The information about build volume exceedance as well as part intersections form the inequality conditions. Using metaheuristic optimization algorithms all information can be combined in a common penalty function to evaluate the current solution with a specific set of decision variables which is used to find a new solution in a further optimization step. This procedure is repeated until a predefined termination criterion is met such as a given number of iterations or a quality criterion. Therefore, the exact optimization procedure depends on the type of optimization algorithm and its settings. As a result, the optimization algorithm finds an optimal solution according

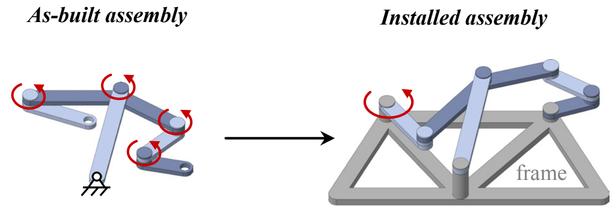


Fig. 2. Differences in DOF between as-built and installed assemblies.

to the predefined conditions. In a final step, the toolpaths for the chosen, optimal solution can directly be used for the AM.

3.2. Integration of CAD software and build time and support material quantity analysis

In order to guarantee the applicability of the method, it is useful to integrate a suitable CAD software and a slicing software. In doing so, the product developer can use the familiar CAD software so that a remodeling of the assembly is not required. Thus, manual mistakes are reduced by the direct link between the optimizer and the CAD software. By coupling the optimization with a suitable slicing software, the estimation of the build time as well as the support material is performed on basis of the generated toolpaths. Although detailed-analysis-based build time estimation techniques are usually more time consuming than parametric-based ones they can precisely evaluate the objectives for the real design of the assembly with its part orientations and positions.

The adaptation of the general optimization process from Fig. 3 to a CAD-integrated optimization process using a detailed-analysis-based estimation technique is shown in Fig. 4. Before the optimization can be started, the translational and rotational DOFs of the individual links must be parametrized so that the optimizer can modify these values to rearrange the assembly. So the optimizier selects a current set of orientations and positions for the individual parts $\vec{v}_{\mathrm{i,red}}$ which is directly passed to the CAD system to update the assembly considering the predefined mating conditions in the CAD model. In general, a common CAD system offers the opportunity for a global intersection check of the assembly. Moreover, the dimensions of the whole mechanism can be used to check if the current configuration exceeds the build volume of the manufacturing machine.

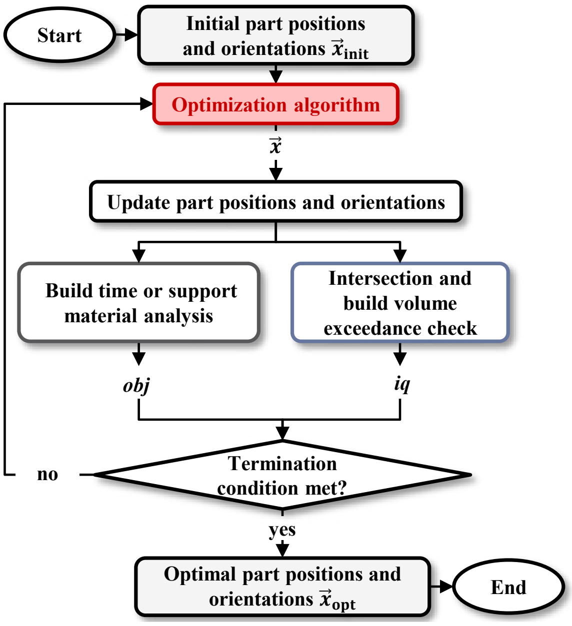


Fig. 3. General framework for the single-objective build time or support material quantity optimization.

In the next step, the model according to the current set of decision parameters is exported in a suitable exchange file format, e.g. STL (Standard Tesselation Language) or OBJ (Wavefront Object), and is transferred to the slicing software for generating the toolpaths. These are used in a further step to estimate the required support material or the build time using the integrated build time estimator. Summing up, the CAD system enables the adjustment of the model as well as the export for the examination of the inequality conditions while the slicing software calculates the objective.

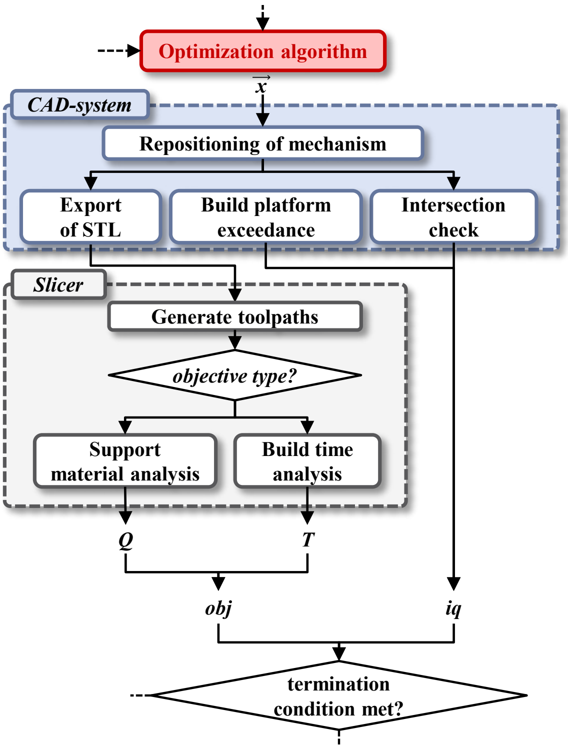


Fig. 4. Procedure of CAD-integrated build time and support material quantity optimization using slicing software for detailed-analysis-based build time estimation.

4. Application

In the following, the presented method is applied to a case study. By choosing the printer Ultimaker S5, it is possible to print support structures with water-soluble filament with an additional second extruder and thus enables the AM of non-assembly mechanisms.

4.1. Presentation of the case study

In order to show the applicability and the benefits of the optimization method, a planar 3RRR manipulator is used as a case study. According to Fig. 5 three arms are attached to the triangular base plate of the mechanism, each consisting of two links. By fixing the base plate, six rotational DOFs are unconstrained and thus have to be parameterized in the CAD model. Due to the layerwise build process, the geometric accuracy of the guiding surfaces of the revolute joints are influenced by their orientation. To avoid staircase effects, the mechanism is positioned flat on the platform so that the axes of the joints are equal to the build direction z (see Fig. 5).

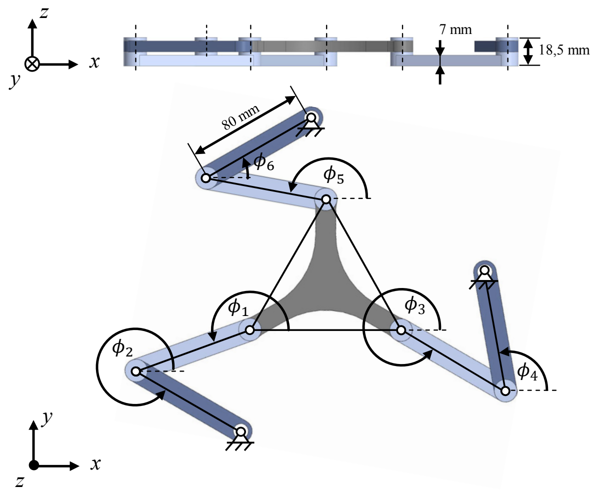


Fig. 5. Parameterized CAD model of 3RRR manipulator in initial configuration.

4.2. Optimization

As it is known from section 3, any stochastic optimizer, which can handle nonlinear constraints, is suitable for the build time and support material quantity optimization. In this contribution, a Genetic Algorithm is examplarily applied to the given case study. Although metaheuristic algorithms are problem-independently applicable, the results are strongly dependent on the settings of the optimizer, which have to be chosen with respect to the given optimization problem. Based on previous studies, the population size was set to 50, the number of generations to 200. An average relative change of 0.01 in the best fitness function value over 100 generations was defined as a suitable termination criterion to achieve reproduceable and reliable optimization results. For all other parameters, which define the selection, mutation and reproduction processes, the default settings were used.

As it is illustrated in Fig. 4, it is expedient to integrate a slicing software and CAD software in the optimzation process. In this contribution the optimization is done in MATLAB R2017a using the CAD software PTC Creo® Parametric 4.0 and the slicing software Ultimaker Cura v3.3.1.6. The settings for the process parameters are equivalent to the default values for the printer using Cura.

4.3. Discussion of the results

Based on the parameterized CAD model, the mechanism was both optimized for build time T and support material quantity Q. The results are summarized in Table 1.

Table 1. Optimization results for the given case study.

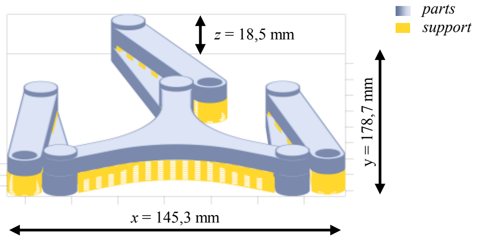
Status	$Q(\vec{\phi})$ in mm^3	$T(\vec{\phi})$ in s	ϕ_i in °
Initial	9479	25306	200, 330, 330, 100, 170, 30
Q-optimal	**7794**	24906	96, 265, 93, 284, 105, 296
T-optimal	9163	**24783**	218, 296, 309, 141, 234, 152

Both solutions are valid since they satisfy the constraints: There are no part intersections and both optimized mechanisms fit in the build volume of the printer B (x = 330 mm, y = 240 mm, z = 300 mm), as it can be seen in Fig. 6.

The optimum for the support material quantity can easily be verified. By turning in the outer links as far as possible, the overlap area of the individual components is increased and the support material quantity is reduced to a minimum (see Fig. 6 a)). The time-optimal configuration in Fig. 6 b) is less obvious. To reduce the required build time, the optimizer tries to realize long extrusion paths while minimizing the extrusion-free travel times. Hence, the time-optimal arrangement of the mechanism strongly depends, inter alia, on the type of the support and the infill as well as the print and travel velocities. Especially at this point, it becomes clear that by using the presented method the user is assisted in identifying the often not apparently optimal arrangements of moveable assemblies.

In this contribution, the objectives were both seperately optimized in a single-objective optimization. Since the correlation between the objectives strongly depends on the design of the mechanism with its joints and DOFs and the applied machine with its process parameters, they can not readily predicted. In order to find an optimal solution for both build time and support material quantity, multi-objective optimization techniques should be taken into account. Thus, it makes sense to include the required time effort for the removal of support material as a function of the support material quantity in the optimization procedure.

a) Q-optimal



b) T-optimal

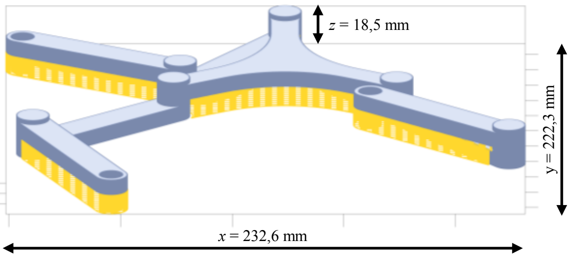


Fig. 6. Optimized variants of the 3RRR manipulator: a) for the support material quantity Q, b) for build time T.

5. Conclusion and outlook

For a profitable implementation of AM in industry, the build time and the material quantity must be kept as low as possible. In addition to the settings of the various process parameters, build part orientation and part geometry, the arrangement of the individual parts plays an important role in the manufacturing of as-built assemblies. For this reason, a novel method was presented that allows non-assembly mechanisms to be automatically arranged minimizing the support material quantity or build time. The integration of a CAD software and a slicing software enables an automated optimization taking into account a preselected AM machine. The exemplary application to a 3RRR planar manipulator has demonstrated that optimizing the part orientation of the individual moveable parts can significantly reduce the required build time and support material quantity. Depending on the mechanism and the number and type of integrated joints, the two objectives are more or less in conflict. Therefore, further research activities should extend the method to a multi-objective build time and support material quantity optimization.

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